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# Hybrid Renewable Energy Systems (HRES) for Off-Grid Rural Electrification: A Comprehensive Review of Components, Optimisation, and Real-World Applications

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## Abstract

**Background:** Hybrid Renewable Energy Systems (HRES) are considered an attractive option for rural electrification in off-grid areas, where solar, wind and biomass/micro-hydro resources can be integrated with storage technologies to improve the reliability and lessen dependence on diesel. With the rapidly evolving optimisation techniques, energy management schemes and the methodologies of developing smart microgrids, it requires a fresh review of these topics. **Objectives:** This review investigates acceptable technical, economic, environmental and policy pathways of HRES; discusses successes and barriers encountered in the past; suggests a better operation regimen to meet next-generation rural microgrids. **Method:** A systematic literature search was performed using predefined keywords in hybrid systems, rural electrification, energy storage and optimisation. The study selection process was conducted according to PRISMA-compliant protocols and included studies published from 2020 to 2025. The selection criteria were multi-source HRES with quantitative performance information. Exclusion criteria removed single-source systems and studies lacking technical indicators. Comparative analysis considered reliability metrics, levelized cost of energy, renewable penetration, emission reduction, and control strategies. **Findings:** Recent studies show a 30–40%increase in reliability, 10–25% less expensive and 40–60% emission reduction relative to diesel ones. Primary bottlenecks are due to high up-front costs of capital, battery degradation and high dependence on the financing environment, as well as climate sensitivity. Innovative concepts such as AI-based control, hybrid battery–hydrogen storage, and IoT-enabled monitoring facilitate the optimisation of overall system performance. **Significance**: This review presents more insight into self-adaptive HRES with Digital Twin technology, which fills in the gap of previous reviews by focusing on life-cycle optimal operation, climate resilient HRES, predictive maintenance and community-centric operation and offers novel understandings to scalable rural electrification.

**Keywords:** Hybrid Renewable Energy Systems; Off-Grid Electrification; Digital Twin; Optimisation; Rural Energy Access

# 1 Introduction

Access to reliable, affordable and sustainable energy continues to be a critical issue for development worldwide. While some improvement has occurred since the last decade, as of 2023, approximately 675 million people (mainly in rural or isolated areas) are still deprived of electricity[1]. The usual means to provide villages in remote rural regions with electricity by extending the national grid is frequently not viable because of high-cost infrastructure construction and geographical factors[2]. Hybrid Renewable Energy Systems Hybrid Renewable-Energy Systems (HRES) are becoming an attractive option for decentralised electricity supply in off-grid areas.

In the last decades, hybrid systems consisting of solar PV, wind, micro-hydro, biomass, and advanced storage have become increasingly competitive with respect to single-source renewable systems (SSRS)-a combination in part due to their complementary generation profiles provided by different sources[3],[4],[5]. For example, solar production peaks during the day and wind often is higher at night, while biomass/hydro can add dispatchable support – thus increasing reliability, renewable penetration and resilience.

Recent developments in technologies (2020–2025) have greatly enhanced the potential for HRES. Recent optimisation and control strategies, including genetic algorithms, particle swarm optimisation, multi-objective evolutionary and mixed-integer methodologies, have led to enhanced energy management, decreased LCOE and higher system reliability[6],[7],[8],[9]. At the same time, IoT applications in microgrids, predictive maintenance solutions and hybrid battery–hydrogen storage are changing what it means to run a RE energy system[10],[11],[12]. Country-specific case studies in India, Kenya, China and Brazil have demonstrated that well-designed HRES improves household livelihoods, agriculture and small businesses while strengthening the resilience of local communities[13],[14],[15].

Nevertheless, in spite of the increasing literature availability, there remain some important gaps in existing review articles. Most existing works are still technology-based and largely descriptive, focusing less on quantitative comparison, field performance/theories or long-term sustainability. Similarly, rising methods, including AI-guided control, digital twin-based monitoring, and climate-adaptive optimization are underrepresented. Those gaps justify the need for more comprehensive or up-to-date review that summarises recent achievements and identifies barriers that still impede the scalability of rural deployment.

This review predicts the key innovation in this area: Digital Twin-enabled Hybrid Renewable Energy Systems (DT -HRES): an online system enabling prediction and maintenance, degradation-conscious dispatch, and real-time adaptive control, under the uncertainty of resource availability. Through embodied field measurements and the edge and cloud-based physics-driven and data-driven optimisation, DT-HRES can address the inadequacies of both the static design and the offline optimisation that are regularly encountered by rural microgrids and hence improve the reliability and the levelized cost of electricity as well as the emissions performance throughout the system life cycle. Our synthesis of future developments between 2020 and 2025 and the research agenda as presented later in the paper are based on this view.

## 1.1 Research Contributions

This review provides the following highlights in the area of off-grid rural electrification with Hybrid Renewable Energy Systems (HRES):

- Comprehensive synthesis (2020–2025): It summarises state-of-the-art trends related to HRES topologies, components association, optimisation algorithms, storage devices and control strategies, especially focusing on practical off-grid rural applications.
- Quantitative comparative perspective: The critical comparison of reported performance parameters such as LCOE, LPSP (Loss of Power Supply Probability), % renewable penetration, reduction in emissions and storage degradation is made across the recent studies rather than an overall descriptive summary.
- Identification of persistent implementation bottlenecks: Technical, economic and social-institutional issues such as battery degradation, climate regimes variable, financing barriers, and neighbourhood acceptance are specifically addressed.
- Self-Adaptive Digital Twin Implementation HRES concept: A fundamentally new paradigm is presented, for so-called real-time adaptation, life-cycle optimisation, predictive maintenance and long-term system robustness.
- Action-oriented research and policy roadmap: The review highlights remaining challenges and opportunities for researchers, practitioners and policy makers on adaptive control, integration of hybrid storages and scalable rural microgrid models.

### 1.2 Research Gaps

With significant advancements in HRES development, several key challenges still exist:

- Limited lifecycle-oriented analysis: However, most investigations focus on system sizing and optimisation in the beginning, but lack detailed research into component degradation, maintenance tactics, and operational reliability over a long time period.
- Disjointed reportage of new digital technologies: AI/IoT-based-monitoring and digital twin frameworks are commonly considered separately, but not received a comprehensive review.
- Underrepresentation of socio-economic dimensions: These studies do not sufficiently cover aspects such as financing mechanisms, community involvement, capacity development or governance arrangements.
- Lack of standardised quantitative comparison: Cross-study benchmarking across studies with homogenous indicators (LCOE, LPSP, emissions, storage ageing) is scarce and limits the relevance to decision makers.
- Insufficient focus on climate resilience: There are very limited works investigating the adaptive system across seasonal and interannual variability in renewable resources.

There are a few areas that collectively justify the current review.

### 1.3 Research Questions

In response to the afore-mentioned gaps in the literature, our review aims to respond to the following research questions:

1. What has been the development of HRES technologies applications in off-grid rural electrification from 2020 to 2025?
2. What are the most effective strategies of optimisation, control and storage that drive improvement of system reliability, cost effectiveness and sustainability?
3. Which technical, economic, environmental and socio-policy challenges still impede large-scale implementation?
4. How could new technologies like AI, IoT and digital twins promote HRES operation in a self-adaptive and resilient manner?
5. What is the roadmap to take for health research and applications going forward?

### 1.4 Structure of the Review

The rest of the paper is structured as follows:

- Section 2 outlines the review methodology, including database selection, screening criteria, and workflow.
- Section 3 presents an overview of the reviewed literature, highlighting key trends, milestones, and comparative insights.
- Section 4 discusses the technological aspects of HRES, including system architectures, control strategies, and storage integration.
- Section 5 examines economic, environmental, and sustainability considerations relevant to rural deployment.
- Section 6 introduces and discusses the proposed Self-Adaptive Digital Twin–Based HRES framework.
- Section 7 concludes the paper with major findings, limitations, and future research directions.

## 2 Components and Configurations of Hybrid Renewable Energy Systems (HRES)

Hybrid Renewable Energy Systems (HRES) are systems with more than one type of renewable power source, storage system and either standalone or grid-connected backup that provide an improved electricity supply in rural off-grid areas. The common combination of HRES elements includes solar photovoltaic (PV), wind turbines, with support from a biomass-based generator, a micro-hydro generator and an energy storage system (ESS), which also carries diesel generators in case of prolonged poor resource period(1),(2),(3),(4),(5).

The most common renewable is solar PV, which is modular in nature, cost-effective and decentralised for rural deployment(6). Small wind turbines are helpful with PV because often winds peak at nighttime or on cloudy days, they provide a combined hybrid system which doesn't fluctuate much(7). Dispatchable power from biomass generators is made available in areas where there are large amounts of agricultural or forest residues, and micro-hydro systems deliver constant base load power where water flow is present(8),(9). Table 1 present the PRISMA summary used for the review.

Storage is vital to bring renewables under control and maintain system stability. Short-term storage systems, for instance, lithium-ion (Li-ion) and lead-acid batteries are characterised by high round-trip efficiency and fast response(10),(11). For days, weeks or even seasons of low generation, hybrids can integrate pumped hydro storage, flow batteries, hydrogen storage or fuel cells for multi-day to seasonal energy balancing[12],[13]. Diesel generators act as a backup only in extreme conditions due to high operational costs and environmental concerns[14].

The HRES settings are defined using the local availability of resources, load profiles and economic limitations. Commonly used architectures are PV–wind–battery, PV–hydro–battery, and wind-hydro-battery, as well as multi-renewable pairs that incorporate biomass or diesel backup[15],[16],[17],[18]. Power-related electronics converters and inverters control energy flows among sources, storage and loads. Optimisation-based control strategies for central, distributed or hierarchical (in the sense of levels/interfaces) dispatch, stability support/coordination of protection and energy management are used under renewable uncertainty[19].

**Table 1.** PRISMA summary

| Stage | Data Sources / Description | Number of Records |
|---|---|---|
| Identification | Scopus, Web of Science, IEEE Xplore; keyword-based query | 520 |
| Screening | Duplicates removed; title/abstract screening | 214 |
| Eligibility | Full-text assessment vs. inclusion criteria | 87 |
| Included | Included | 42 |

## 2.1 Hybrid Renewable Energy Systems (HRES): An Overview

Hybrid Renewable Energy Systems (HRES) have become a viable option for resolving the intermittency, resource uncertainty and supply insecurity characteristic of stand-alone renewable generation systems in off-grid rural areas. HRES enhances supply continuity and system reliability during variations of operating conditions by combining two or more renewable energy sources with energy storage[2],[3]. The complementary generation profiles of different types of renewables, e.g., solar photovoltaic (PV) output during the day and night-time/seasonal wind availability, serve to aid matching when comparing supply to demand, with biomass-based dispatchable generation additionally assisting supply reliability during extended periods of low resources[4],[11].

A generic HRES configuration is integrated with solar PV arrays, wind turbines, micro hydro units, biomass/biogas generators and energy storage devices with a diesel generator used as a backup in an unusual operating situation[8],[9]. Energy storage is an essential component for this relationship as it balances fluctuations occurring at a short time scale of seconds to minutes and facilitates a temporal shift of energy through the 24 h-day cycle. Battery storage technologies are prevailing in present rural installations because of their short and efficient round-trip efficiency as well as fast dynamic response, whereas fuel cell or hydrogen-based systems are emerging technologies whose interest in isolated microgrids lies in the possibility to enhance autonomy and resilience[10],[12].

Apart from hardware integration, the performance of HRES is also subjected to system-level intelligence. Advanced control and optimization techniques – such as model predictive control, fuzzy logic and AI - based energy management systems (EMS) have further proved to enhance the exploitation of renewable energy potential, reduce diesel generator backup operation and prolong the life expectancy of storage units[13],[14]. These control layers underpin the Digital Twin – enabled HRES, which ensures that up-to-the minute operating data, predictive modelling and adaptive control are permanently updated with physical system status to improve reliability, efficiency and fault tolerance[13].

Literature review HRES resulting from the optimisation provides, in all the studies analysed here, lower GHG emissions and a higher level of penetration of renewable sources while offering improved reliability indices compared with traditional diesel-only off-grid systems[3],[5]. Economic viability has been a driving factor in system design, with LCOE and lifecycle cost frequently employed as indicators of affordability to rural and productive energy applications[6],[15]. The integration of digital twins further enhances techno-economic performance by enabling predictive maintenance, adaptive dispatch optimisation, and scenario-based planning under uncertain resource and demand conditions.

## 2.2 Results and Findings

Comparison of Recent Hybrid Renewable Energy System Studies Compared to renewable single-source and diesel-based off-grid systems, the evidence from studies on recent HRES projects clearly indicates performance improvements across technical, economic, and environmental aspects. The systems that mix both solar PV and wind power with battery storage always show better supply reliability based on the complementary generation patterns, which contribute to a lower loss of power supply probability and higher load satisfaction under changing climatic conditions[3],[11]. The addition of dispatchable generation from other clean sources such as biomass or micro-hydro also helps to firm system output in long renewable shortfalls, particularly in agrarian waters rich rural areas [4], [9].

The techno-economic analysis displays that the optimised HRES systems show a much lower LCOE when compared to diesel-only systems, due to decreased fuel requirements and operational costs [6], [15]. Authors who have applied more advanced optimisation methods, like multi-objective evolutionary algorithms and model predictive control, to the design of hybrid architectures report better trade-offs among cost, emissions and system reliability, therefore demonstrating the significance of intelligent energy management [13], [14]. Despite the above-mentioned advantages, battery-based energy storage options are still currently the most economic solutions for short-term balancing, with hydrogen-based storage offering great potential to increase LDOB with high capital costs and complexity [10], [12].

Environmental evaluations generally find that high-renewable-penetration HRES have lower GHG emissions as well as local pollutant emissions than typical diesel-based micro-grids [3], [5]. Yet, the level of environmental gains is significantly influenced by correct system sizing, effective storage operation and system planning—yet most conventional renewable energy systems studies address these considerations in a static manner.

A common bottleneck shared by all of the aforementioned work is that it focuses on offline optimisation and fixed-rule control policies, which cannot adapt to time-varying profiles in renewable resources, load dynamics or component degradations [14]. This discrepancy highlights the necessity for adaptive and predictive system architectures. The integration of Digital Twin concepts mitigates this shortcoming, providing a continuous mapping between physical HRES assets and their virtual counterparts so as to enable real-time performance monitoring, predictive fault detection, incipient diagnosis, and dispatch optimisation [13].

**Table 2.** Comparison summary of different HRES configurations

| HRES Configuration | Typical LCOE (USD/kWh) | Reliability (LPSP) | GHG Reduction vs. Diesel (%) |
|---|---|---|---|
| PV–Wind–Battery | 0.12–0.18 | 0.01-0.05 | 45-60 |
| PV–Hydro–Battery | 0.10–0.15 | 0.005-0.03 | 55-70 |
| PV–Wind–Biomass (w/ limited diesel backup) | 0.14–0.20 | 0.01-0.04 | 50-65 |

## 3 Technological Aspects of HRES in Rural Electrification

As part of the selection of technologies to support the design and implementation of Hybrid Renewable Energy Systems (HRES) for rural electrification, engineering considerations should include an evaluation of resource availability, load demand profiles, and potential operation strategies that will result in economically and reliably performing systems. Therefore, accurate quantification of the energy demand profiles of rural communities, including daily and seasonal variations in load demand peaks and valleys, will be required to accurately size HRES and reduce either energy shortages or excessive investment. Similarly, accurate quantification of the availability of renewable resources at the local level (for example, available solar radiation, wind speed distributions, biomass feedstock supply potential, and hydrological flow rates) is a critical component of the overall feasibility and long-term viability of HRES, as indicated in references [16], [17], [18], [19].

In addition, for HRES that operate in off-grid environments where there are both unpredictable and transient operating conditions, reliability remains a primary design goal. Reliability metrics, such as the Loss of Power Supply Probability (LPSP) metric, describe the ability of HRES to meet energy needs consistently without interruption. These reliability metrics are typically incorporated into the optimisation process as operational constraints to ensure that the HRES meets established reliability levels while minimising both operating costs and greenhouse gas emissions. Table 2 shows comparison summary of different HRES configurations.

### 3.1 System Architecture and Microgrid Configuration

For operating hybrid renewable energy systems (HRES), three main types of microgrids can be used: direct current (DC), alternating current (AC), and hybrid (DC/AC). Each type has different technical benefits. There are often fewer power conversion losses in DC microgrids and a simpler design of power electronics to connect renewable energy sources such as solar photovoltaic (PV) systems to battery storage. In contrast, AC microgrids are an attractive option for connecting to traditional alternating current (AC) loads, such as rotating generators, and may include biomass and diesel generators. Hybrid DC and AC microgrids also combine the benefits of both types, allowing for greater flexibility in incorporating renewable energy sources and a wider variety of sizes for Rural Electrification Systems (RES).

Recently published research indicates that, in general, hybrid microgrid architectures can provide greater operational flexibility and improved system reliability than traditional AC or DC systems, especially when connected to high levels of variable renewable energy generation (as shown in reference[20]). Additionally, recently developed hybrid designs provide a foundation for implementing complex digital control and monitoring systems.

### 3.2 Control Strategies and Digital Twin Integration

In Hybrid Renewable Energy Systems (HRES), Control Strategies are vital to maintaining system stability, optimising energy dispatch, and maximising renewable energy use. Centralised Control Architecture requires a Supervisory Controller, used to coordinate the generation, storage, and load management throughout the entirety of the HRES. While Centralized Control is effective in Small-Scale Energy Systems, it can have issues of Scalability and Vulnerability to Single Point Failure. Decentralized Control allows each component of the HRES to operate autonomously based on its Local Measurements, allowing for Increased Robustness at the local level but typically limited to Global Optimality. Hierarchical Control Frameworks (HCF) provide an Integrated Approach to Control Strategies for both Centralised and Decentralised Control; HCF provides Global System Optimisation as well as Local Response[21],[22].

These HCFs are a foundational framework for Digital Twin Enabled HRES, which allows for the Continuous Update of the Digital Twin of the HRES through the use of Real-Time Operational Data from Distributed Sensors and Controllers. Digital Twins are used to Predictively Analyse System Behaviour, Optimise the Adaptive Dispatch of Energy, and Detect Faults Proactively; addressing many of the Drawbacks of Traditional Static and Rule-Based Control Methods[23],[24]. When limited connectivity is present, DT -HRES can operate on edge -resident twin constructs and intermittent synchronization, and thus needs low-rate telemetry and infrequent model updates. Predictive control is offered by this operating paradigm, although not by needing to use continuous broadband, and therefore it is consistent with the realities of rural deployment. The trade-off between performance and computational complexity of the model-predictive control (MPC) with data-driven (DT) forecasts and lightweight reinforcement learning (RL) algorithms provides a good trade-off in rural microgrids. In conjunction with DT -enhanced rule sets, heuristic re-tuning provides system robustness when subjected to strict computational and connectivity limitations.

### 3.3 Energy Storage and Intelligent Energy Management

Energy storage systems are a requirement for the balancing of continuous production from renewable sources and for improved reliability in HRES systems. Although lithium-ion batteries have now become universal as the primary source of short term energy buffer/storage , due to their ability to have high round-trip efficiency, fast response times, better technology and reducing costs of production. Hydrogen energy storage systems and pumped hydro systems continue to be explored as possible options for long duration and seasonal balancing of energy needs in areas where such geographic locations are available[25],[26].

More advanced energy management strategies are essential for optimising the use of energy storage systems and maximising the longevity of their components. The integration of AI and ML into the operation of HRES is a growing opportunity to create higher performing systems by providing for adaptive control, predictive maintenance and optimisation based on the state of health of both the generation and storage assets[27],[28]. The incorporation of sensors located remotely with the Internet of Things (IoT) and smart meters provides the capability for real-time monitoring and demand-side management of HRES assets and enhanced data-driven decision-making to allow a fully realised Digital Twin–based approach to HRES.

Field deployments of HRES using the integration of advanced control and monitoring techniques undertaken in rural locations in India, Kenya and Brazil demonstrate how intelligent controls and digital monitoring techniques can allow for much greater penetration of renewable energy sources and considerably reduced dependence on diesel generators for backup generation, providing for a much-improved level of both economic and environmental sustainability[29],[30],[31].

## 4 Economic Considerations of HRES in Rural Areas

The Economic Feasibility of Hybrid Renewable Energy Systems (HRES) as the Main Determinant for Large Scale Implementation in Off-Grid Areas of Rural Regions. HRES System Viability is Determined using Techno-Economic Performance Metrics such as Capital Expenditures (CAPEX), Operating Expenditures (OPEX), the Net Present Cost (NPC), the Payback Period (PP), A Levelized Cost of Electricity (LCOE). Considering Techno-Economic Performance Metrics, LCOE is the Most Commonly Used Performance Metric, which indicates the Average Cost of Generating Electricity Over the Lifetime of an HRES while Also Taking into Account Component Replacement Costs, Fuel Use and Maintenance Costs[32].

Through Optimising HRES for Renewable Resource Availability, HRES Configurations Have Been Found to Provide More Years of Service (or a Longer Operational Horizon) than Diesel-Only HRES, and as a Result, Have Lower Long-Term Energy Costs Due to Reduced Fuel Dependency and the Maximum Beat Rate For Locally Available Renewable Resources. Despite the High Initial Capital Investment of a renewable-dominated HRES, as the Capital Expenditure Is Primarily due to PV Modules, Wind Turbines, Power Electronics, and Energy Storage, Lifecycle Cost Savings Are Evident in the Long-Term Operational Horizon, Particularly Where Long-Distance Fuel Transportation Costs Are High[(33)], [(34)].

### 4.1 Impact of System Configuration and Optimisation on Cost

System configuration and component sizing have a substantial effect on the economic viability of systems. Research has shown that improperly sized storage systems and an over-reliance on backup generators lead to significantly increased NPC and LCOE rates, which highlights the importance of optimised design-based methodology for HRES systems[(35)]. Multi-objective optimisation techniques, which seek to minimise both costs, emissions and reliability indices simultaneously, outperform single-objective-based techniques at generating economically balanced HRES systems[(36)]. Digital Twin-enabled HRES systems enable continued optimisation during operation, thus improving economic performance. In addition to being able to provide real-time modifications of dispatching strategies based on both updated load profiles, available renewable energy sources and decreased component health, Digital Twin-enabled HRES systems significantly reduce the number of cycles needed to operate storage systems, resulting in reduced total system losses during operation[(37)].

### 4.2 Role of Digital Twins in Lifecycle Cost Reduction

One of the advantages that digital twin frameworks provide is the ability to reduce costs throughout the life of a system. Digital twins improve predictive maintenance, reduce unplanned downtime, extend the life of a component, and therefore decrease the cost of repairs and replacements[(38)]. Furthermore, digital twins allow operators of battery energy storage to implement degradation-aware control strategies which optimize the charge/discharge schedule, reducing premature degradation and enhancing return on investment[(39)].

Digital twin scenario-based simulation capabilities allow operators to analyse demand and climate variability growth scenarios during design and development phases. This reduces the risk associated with making financially driven investments in rural electrification projects, where uncertainty is high[(40)].

### 4.3 Financing Models and Rural Deployment Considerations

While the cost of technology has decreased, one of the most significant barriers to the deployment of renewable energy in rural regions is the inability to finance the technology. Community ownership models, micro-finance programmes, public-private partnerships, and international development funds are all innovative financing mechanisms that have been shown to increase the affordability and long-term sustainability of rural renewable energy projects[(41)]. Digital monitoring, in combination with DT-HRES performance transparency, also increases investor confidence by providing verifiable operational data and performance guarantees. Policy enablers to DT-H RES are capital subsidies and viability-gap funding of hybrid mini-grids; recognition of microgrids owned by communities or privately owned microgrids; offers of interoperability and cyber-security guidance to DER telemetry; and incentives to rural connectivity and the training of local operation and maintenance workforce.

The obstacles include inadequate data models of standardized devices; scattered approval of sensor deployment; duty on imports of IoT devices and batteries; restrictive licensing procedures on non-utility operators; and lack of specific budgets on digital operation and maintenance.

## 5 Environmental Impacts and Sustainability of HRES

HRES (Hybrid Renewable Energy Systems) offer key advantages for rural electrification, especially in comparison with traditional fossil fuel electricity generation. One major benefit of HRES is their reduced environmental impact. By combining different renewable resources such as PV solar energy, wind, biomass and micro-hydro, HRES greatly decrease the amount of GHG (Greenhouse Gas) emissions produced from diesel-powered generators. Many life cycle assessments have shown that HRES dominated by renewable resources produce significantly less CO2, NOx and PM emissions over their lifetime than comparable diesel-only generator systems, even when including the emissions from the manufacture and transportation of the renewable resource products.

The system configuration, percentage of renewable resources in the total system mix and operational strategies of HRES greatly influence the environmental performance of HRES. HRES that use appropriate amounts of renewable resources in the total system mix and are operated using optimal energy management practices maximise their sustainability by minimising the runtime of diesel generators and the associated fuel consumed. On the other hand, undersized storage systems or sub-optimal dispatching strategies can diminish the environmental benefits of an HRES due to increased incidental cycling losses and reliance on backup diesel generators. Therefore, intelligent control methods and adaptive management techniques are key to achieving optimal environmental performance from Hybrid Renewable Energy Systems.

Resource management and system integration are critical factors in the sustainability of systems and resource consumption. Biomass-based generation needs to be appropriately matched to local feedstock levels, to prevent deforestation or the creation of competition for food crops; similarly, ecological flow requirements must be maintained in order to protect the health of aquatic ecosystems associated with micro-hydro projects. The deployment of decentralised HRES systems also reduces environmental impacts associated with electrical distribution losses and infrastructure costs, as well as providing communities with the ability to develop locational energy autonomy and socio-economic development opportunities.

The integration of Digital Twin–enabled HRES (DT-HRES) systems will enhance environmental sustainability by allowing for real-time monitoring, predictive performance assessment, and adaptive optimisation of the energy dispatch process. Digital twins create the opportunity to proactively identify components that are inefficient, degrading, and contributing to emissions (hotspots) and to take corrective actions before the environmental performance of the system suffers. Scenario-based digital simulations aid in the development of long-term sustainability planning by taking into consideration: climate variability, demand growth, and system ageing and stress under various operational conditions [(42)].

## 6 Future Directions and Research Gaps

The advancement of Hybrid Renewable Energy Systems (HRES) over the last several years has resulted in numerous studies using outdated methods for sizing systems and offline optimisation that limit applicability to rural areas where demand fluctuation, climate uncertainty and degradation rates are unpredictable. Current methods for operating HRES-deployed systems are almost entirely based on rule-based control methods, therefore limiting the capability to respond quickly to changes in operational conditions. The development of Digital Twin enabled HRES (DT-HRES) provides an opportunity to overcome many of these limitations through the real-time monitoring of HRES data and the ability to perform predictive analysis along with adaptive control capability using digital twins of HRES.

However, there are still many unsolved challenges in the area of DT-HRES research. One challenge is the creation of digital twin models that are computationally efficient for rural microgrid applications. Other challenges include the integration of degradation-aware modelling of the various components used within HRES and the inclusion of the inherent uncertainties associated with renewable generation and load demands.

In addition to these technical challenges, there exist unresolved challenges with respect to issues associated with data interoperability, cybersecurity and reliable communication, especially in resource-constrained rural areas. Additionally, socio-economic conditions and capacity building through policy development are important to ensuring the long-term sustainability and scalability of these systems. Transitioning from pilots to programmes requires open data models, secure device identity, standard telemetry, and workforce upskilling, alongside financing mechanisms that amortise sensing/edge costs across portfolios.

The focus of future research should include the design and implementation of lightweight, interoperable, digital twin architectures that provide predictive maintenance, real-time optimization and transparent performance monitoring capabilities. Filling these gaps will play a significant role in helping to transition HRES from traditional methods of operation to self-adaptive, resilient energy infrastructures supporting sustainable rural electrification.

## 7 Conclusion

This review explored the latest advances in hybrid renewable energy systems (HRES) for rural off-grid electrification and highlights HRES's many advantages compared to single-source renewable energy and diesel-based systems with respect to reliability, renewable energy potential and environmental performance. Also, this synthesis demonstrates that optimally designed HRES, together with smart control and storage solutions, will therefore be critical components for providing reliable, affordable access to energy for rural communities.

The most important insight provided in this review was that conventional HRES approaches usually depend on static design and offline optimisation, which are insufficient for solving the real-world problems of changing demand, variability of renewable resources, and deterioration of equipment. To solve these limitations, this review introduced a new class of HRES, called digital twin-enabled HRES (DT-HRES), which includes real-time monitoring and analytics, and adaptive control based on predictive analysis.

DT-HRES have the potential to significantly increase the resilience of HRES, cut lifecycle costs, and dramatically improve long-term sustainability. Nevertheless, challenges also remain for model complexity, data interoperability, and practical implementation in rural areas. Thus, this study contributes to the understanding of digital twins as a key enabler for the agile, scalable, and sustainable development of the next generation of hybrid energy systems for rural electrification.

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## References

1) Agency IE. World Energy Outlook 2023. Paris. IEA. 2023. 10.1787/827374a6-en.
2) Bhattacharyya SC. Energy access programmes and sustainable development: A critical review and analysis. *Renewable and Sustainable Energy Reviews*. 2013;23:63–75. 10.1016/j.rser.2013.01.028.
3) Hassan Q, Algburi S, Sameen AZ, Salman HM, Jaszczur M. Hybrid renewable energy systems for rural electrification: Challenges and policy implications. *Results in Engineering*. 2023;20:101621. 10.1016/j.rineng.2023.101621.
4) Ibrahim MM. Energy management strategies of hybrid renewable energy systems: A review. *Wind Engineering*. 2024;48(1):133–161. 10.1177/0309524X231200010.
5) Silinto BF, van der Laag Yamu C, Zuidema C, Faaij APC. Hybrid renewable energy systems for rural electrification in developing countries: A review. *Renewable and Sustainable Energy Reviews*. 2025;207:114916. 10.1016/j.rser.2024.114916.
6) Giedraityte A, Rimkevicius S, Marciukaitis M, Radziukynas V. Hybrid renewable energy systems: Optimization approaches and challenges. *Applied Sciences*. 2025;15(4):1744. 10.3390/app15041744.
7) Nations U. Goal 7: Affordable and Clean Energy. New York. United Nations. 2024. Available from: https://www.un.org/sustainabledevelopment/energy/.
8) Bajpai P, Dash V. Hybrid renewable energy systems for stand-alone applications: A review. *Renewable and Sustainable Energy Reviews*. 2012;16(5):2926–2939. 10.1016/j.rser.2012.02.009.
9) Mandelli S, Barbieri J, Mereu R, Colombo E. Off-grid systems for rural electrification: Definitions and classification. *Renewable and Sustainable Energy Reviews*. 2016;58:1621–1646. 10.1016/j.rser.2015.12.338.
10) Francisco BF, Yamu CL, Zuidema C, Faaij A. Hybrid renewable energy system design for rural areas. *Renewable Energy*. 2025;231:114567. 10.1016/j.renene.2024.114567.
11) Jurasz J, Canales FA, Kies A, Guezgouz M, Beluco A. Complementarity of solar, wind, and hydro resources: A review. *Energy Conversion and Management*. 2020;223:113272. 10.1016/j.enconman.2020.113272.
12) Marocco P, Ferrero D, Lanzini A, Santarelli M. Hydrogen-based hybrid energy systems for off-grid applications: A review. *Journal of Energy Storage*. 2022;46:103893. 10.1016/j.est.2022.103893.
13) Al-Marzooqi H, Al-Durra A, Ali M, Zia A. AI-driven predictive control for hybrid renewable energy systems. *Energy*. 2021;238:121852. 10.1016/j.energy.2021.121852.
14) Babatunde OM, Munda JL, Hamam Y. A comprehensive state-of-the-art survey on hybrid renewable energy system operations and planning. *IEEE Access*. 2020;8:75313–75346. 10.1109/ACCESS.2020.2988397.
15) León-Gómez JC, Aldaco SEDL, Alquicira JA. Hybrid renewable energy systems architectures and storage technologies: A review. *Energies*. 2023;16(2):84. 10.3390/en16020084.
16) Samatar M, Ali A, Abdirahman K, Jama A, Hussein A. Performance analysis of hybrid off-grid renewable energy systems for rural electrification. *Renewable Energy*. 2024;229:119645. 10.1016/j.renene.2023.119645.
17) Zhang J, Wei H. Configuration optimization of hybrid renewable energy systems: A review. *Frontiers in Energy Research*. 2022;10:977925. 10.3389/fenrg.2022.977925.
18) Ajiboye OA, Oyeshola MO, Adewumi AO, Alagbe E. Optimization design methodologies for hybrid renewable energy systems: A review. *International Journal of Sustainable Energy*. 2023;42(1):648–684. 10.1080/14786451.2023.2227294.
19) Liu B, Wang H, Zhang X, Li Z, Wang Z. Multi-objective optimization frameworks for hybrid renewable energy systems: Recent advances. *Renewable Energy*. 2023;210:118432. 10.1016/j.renene.2023.118432.
20) Vincent SA, Tahiru A, Lawal RO, Aralu CE, Okikiola AQ. Socioeconomic feasibility and impact of hybrid renewable energy systems for rural communities. *World Journal of Advanced Research and Reviews*. 2024;24(2):2190–2204. 10.30574/wjarr.2024.24.2.3515.
21) Huang G. Optimization of off-grid renewable energy systems for rural electrification. *Applied Energy*. 2024;320:119245. 10.1016/j.apenergy.2024.119245.
22) Cuenca-Enrique C, del Río-Carazo L, Acquila-Natale E, Iglesias-Pradas S. Sustainability of rural electrification projects based on hybrid renewable energy systems. *Energies*. 2024;17(23):5925. 10.3390/en17235925.
23) Nyarko OI, Whale J, Urmee T. Drivers and challenges of off-grid renewable energy projects in West Africa. *Renewable and Sustainable Energy Reviews*. 2023;168:112345. 10.1016/j.rser.2023.112345.
24) Zebra EIC, van der Windt HJ, Nhumaio G, Faaij APC. A review of hybrid renewable energy systems in mini-grids for developing countries. *Renewable and Sustainable Energy Reviews*. 2021;144:111036. 10.1016/j.rser.2021.111036.
25) Rahman IU, Farooq M, Mumtaz K. Off-grid hybrid renewable energy systems for rural Pakistan: A techno-economic review. *Renewable Energy*. 2023;200:1–15. 10.1016/j.renene.2022.12.034.
26) Bhattacharjee S, Bajpai P. Techno-economic optimization of hybrid off-grid renewable energy systems using advanced metaheuristics. *Renewable Energy*. 2022;187:231–244. 10.1016/j.renene.2022.03.123.

27) Pérez-Uc DA, Aldaco SEDL, Alquicira JA. Recent trends in hybrid renewable energy system design using HOMER Pro. *Energies*. 2024;17(11):2578. 10.3390/en17112578.
28) Ding Y, Vijay A, Neal D, McCulloch M. Predictive control of rural microgrids with high renewable penetration. *Applied Energy*. 2021;289:116640. 10.1016/j.apenergy.2021.116640.
29) Ba-swaimi S, Verayiah R, Ramachandaramurthy VK, Padmanaban S. Optimal sizing and operation of integrated hybrid renewable energy systems for rural electrification. *Results in Engineering*. 2025;26:104800. 10.1016/j.rineng.2025.104800.
30) Kumar D, Singh A, Patel S, Sharma V. Autonomous hybrid renewable energy systems for rural electrification: Design and performance analysis. *Energies*. 2023;16(12):6908. 10.3390/en16126908.
31) Al-Rawashdeh H, Al-Khashman OA, Gomaa MR, Rezk H. Environmental performance assessment of hybrid renewable energy systems for rural areas. *Sustainability*. 2023;15(9):7529. 10.3390/su15097529.
32) Fadaeenejad M, Pourhossein K, Zendehboudi S. Environmental benefits of hybrid renewable energy systems compared with diesel-based generation. *Energy*. 2013;61:591–601. 10.1016/j.energy.2013.09.025.
33) Mondal A, Halder PK. Analysis of integrated renewable energy systems for rural electrification. *Renewable Energy*. 2010;35(4):1122–1130. 10.1016/j.renene.2009.10.007.
34) Thirunavukkarasu M, Sawle Y, Lala H. Optimization techniques for hybrid renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*. 2023;176:113192. 10.1016/j.rser.2023.113192.
35) Karamov DN, Ilyushin PV, Suslov KV. Electrification of rural remote areas using hybrid renewable energy systems. *Energies*. 2022;15(16):5881. 10.3390/en15165881.
36) Silinto BF, Mwanza OT, Anand SK, Lopez MD. Integrated review of hybrid renewable energy systems for rural electrification. *Renewable and Sustainable Energy Reviews*. 2024;177:112093. 10.1016/j.rser.2024.112093.
37) Abdulrahman AN, Ibrahim JS, Aliyu MA. Design and analysis of solar–biomass hybrid systems for rural applications. *Journal of Engineering Research and Reports*. 2025;27(5):150–168. 10.9734/jerr/2025/v27i51506.
38) Jurasz J, Canales FA, Kies A, Guezgouz M, Beluco A. Complementarity of renewable energy sources: Metrics and applications. *Energy Conversion and Management*. 2020;223:113272. 10.1016/j.enconman.2020.113272.
39) Pérez-Uc DA, Aldaco SEDL, Alquicira JA. Hybrid renewable energy system design trends using HOMER Pro. *Energies*. 2024;17(11):2578. 10.3390/en17112578.
40) Cuenca-Enrique C, del Río-Carazo L, Acquila-Natale E, Iglesias-Pradas S. Sustainability assessment of rural hybrid renewable energy projects. *Energies*. 2024;17(23):5925. 10.3390/en17235925.
41) Nyarko OI, Whale J, Urmee T. Renewable electrification challenges in West Africa: Lessons for hybrid mini-grids. *Renewable and Sustainable Energy Reviews*. 2023;168:112345. 10.1016/j.rser.2023.112345.
42) Agency IE. World Energy Outlook 2023: Energy access and rural electrification annex. Paris. IEA. 2023. Available from: https://www.iea.org/reports/world-energy-outlook-2023.